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RESEARCH DEPARTMENT

THE SELECTION OF THE OPTIMUM H.F. CURTAIN ARRAY FOR A GIVEN TRANSMISSION PATH

Report No. E-074

(1961/15)

THE BRITISH BROADCASTING CORPORATION
ENGINEERING DIVISION

RESEARCH DEPARTMENT

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September 1961

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SUMMARY

The field strength produced by curtain arrays (typical of those used for a high-frequency broadcasting service) has been calculated, and plotted as a function of distance from the receiving site. This form of presentation is more suitable for operational use than the aerial power-distribution diagrams at present employed in the B.B.C., since it gives an immediate indication of the most suitable type of array for a specified range of distances.

1. INTRODUCTION

The most suitable transmitting aerial for a high-frequency (h.f.) broadcasting service is the one which produces as large a field strength as possible over the whole of the required service area. The horizontal angle subtended by the service area determines the horizontal beamwidth of the array. A number of factors determine the vertical directivity of the array; they include the distance to the nearest and farthest points of the service area, the height of the reflecting layer, and the vertical directivity of the receiving aerial.

The vertical beamwidth must be such as to cater both for the range of distances to be covered, and for variations in the height of the reflecting layer.[1] Although the actual trajectories of waves reflected from the ionosphere are very complicated and are continually changing, a working solution may be obtained by assuming that the waves follow triangular paths, between the earth and a spherical ionosphere whose height is assumed to be constant over the whole of the path.* Provided the electron density of the ionosphere is sufficiently high, it is possible to serve any point by a number of different 'modes' involving different numbers of 'hops'. In general, the lowest-angle** mode is the least attenuated, because fewer ground reflexions are involved; this mode is also the last to fail in the case of electron limitation in the ionosphere.

It would therefore appear that the optimum transmitting aerial is one which radiates as much power as possible in the direction corresponding to the lowest-angle mode, and that its beamwidth should be just sufficient to cover changes in angle caused by changes in layer height. Such an array would be very satisfactory for a point-to-point communication service since a similar aerial, sensitive at low angles, could be used for reception. The requirements for broadcasting, however, are somewhat different because the typical listener's receiving aerial is insensitive at low angles. In addition, in order to economize in the number of transmitting arrays required, it is desirable that each should give continuous coverage over a range of distances. It is thus necessary that the transmitting aerial should propagate power in directions corresponding to some of the higher-angle modes.

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*This idealization of the problem may lead to errors in the calculated values of absolute field strength produced by transmitting arrays, but is thought to give a valuable comparison of their performance. The measurements so far made on B.B.C. circuits confirm this view.

**Throughout this report "angle" implies angle to the horizontal.

Since the receiving aerial is usually at a small height above the ground, it may be conveniently taken into account by calculating the field strength at a typical height; the height chosen affects the field strength at the receiving aerial, but if the height does not exceed about half a wavelength, it does not affect the relative performance of different transmitting arrays. The factors which affect the field strength at the listener's aerial are discussed in the next section.

2. FACTORS WHICH AFFECT THE FIELD STRENGTH AT A DISTANT POINT

When propagation takes place via the ionosphere the field strength at the receiving end of the circuit depends on:

(i) the vertical radiation pattern (v.r.p.) of the transmitting aerial.
(ii) attenuation due to path length.
(iii) ground reflexion loss (for multi-hop propagation).
(iv) ionospheric absorption.
(v) ionospheric focusing (convergence gain).
(vi) ionospheric irregularity and the magneto-ionic effect.
(vii) the height of the reflecting layer.
(viii) interference between the direct and ground-reflected waves at the receiving site.

Factor (iii) favours low-angle modes, since the loss at each reflexion is less for the lower angles, and fewer reflexions are involved. Factor (viii) favours high-angle modes, since the reflexion coefficient of the ground is approximately −1 for low angles, both for horizontally- and for vertically-polarized waves. As the other factors are not so dependent on the projection angle, the optimum projection angle is largely determined by a compromise between ground reflexion loss and interference between the direct and ground-reflected waves at the receiving site.

The way in which these factors affect the distant field strength is discussed in greater detail in the following sub-sections.

2.1. The V.R.P. of the Transmitting Aerial

The v.r.p. of the transmitting aerial must be such that it excites the most favourable mode over the whole of the service area. The vertical beamwidth must be such that this requirement is satisfied for all the reflecting layer heights which are likely to be encountered. The array should not radiate unduly in other directions, since unwanted radiation represents a reduction of gain, and therefore of distant field strength.

Since the performance of the transmitting aerial is the main issue under consideration in this report, the effect of its v.r.p. will be discussed in greater detail in Section 4.

2.2. The Attenuation due to Path Length

The intensity of the transmitted signal is inversely proportional to the path length. Over short distances the path length is greatest for the high-angle modes, so that path-length attenuation favours the lower-angle modes. Over distances greater than 5,000 km, however, the path lengths for different modes are substantially the same, and the path-length attenuation is therefore also the same.

2.3. Ground Reflexion Loss

In multi-hop propagation the signal is attenuated whenever it is reflected from the earth's surface. The loss depends on the angle of incidence and polarization of the wave, and on the ground constants. Since the downcoming wave is, in general, randomly polarized as a result of its passage through the ionosphere, equal amounts of power may be assumed to be associated with the vertically- and horizontally-polarized components. Curves calculated on this basis, giving reflexion loss as a function of angle of incidence and frequency, are contained in reference 2; values for 15 Mc/s taken from these curves are reproduced in Fig. 1. The loss is slightly

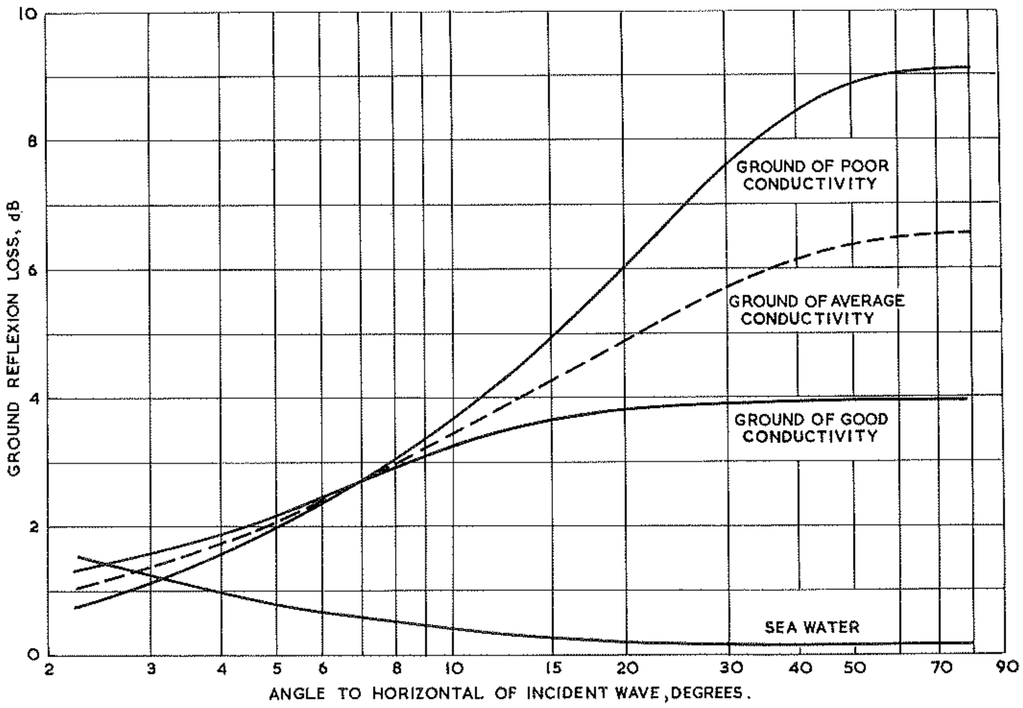

Fig. 1 - Ground reflexion loss for randomly polarized waves

different at other frequencies, but this does not affect the conclusions arrived at in this report.

Fig. 1 shows that, over land, low-angle modes suffer considerably less attenuation than high-angle modes. Not only is the loss smallest at low angles, but fewer ground reflexions are involved. Over sea, however, the total loss is almost independent of the angle of incidence since the greater loss at lower angles is compensated by the smaller number of reflexions involved.

2.4. Ionospheric Absorption

Ionospheric absorption can be divided into two categories, termed deviative and non-deviative absorption. Deviative absorption occurs in the reflecting layer if the frequency is near the maximum usable frequency (MUF); it is smallest for low-angle modes. It will not be considered further in this report because, under normal conditions, the frequency chosen is somewhat less than the MUF and deviative absorption is then negligible.

Non-deviative absorption is usually present but is greatest during the day time; it occurs every time the wave passes through the D layer. On long circuits it is approximately the same for all modes; although low-angle modes pass through the D layer fewer times, they pass through it more obliquely than the high-angle modes. Non-deviative absorption therefore has almost the same effect as the insertion of a fixed attenuator between the transmitter and receiver terminals. Consequently it has a negligible effect on the considerations which determine aerial design, and it will therefore not be considered further in this report.

2.5. Ionospheric Focusing (Convergence Gain)

If the ionosphere and the earth were perfectly smooth the intensity of the signal would be increased by focusing when reflected at the ionosphere, and decreased by an equal amount when reflected at the earth. The focusing effect would be greatest at low angles of incidence, and would therefore favour low-angle modes.

Available evidence[2] shows that ionospheric focusing does not appear to be realized in practice, presumably because of the roughness of the ionosphere. It was therefore neglected in the calculations described in this report. Skip focusing is also neglected because this occurs only at the MUF, which is higher than the frequency normally used for broadcasting.

2.6. Ionospheric Irregularity and the Magneto-Ionic Effect

Measured field strengths are always found to be less than predicted values, even at night, when ionospheric absorption is very small. A number of factors are responsible for the difference. First, the ionosphere is not a smooth reflecting surface and a certain amount of energy is scattered. Second, the earth's magnetic field causes the downcoming wave to be elliptically polarized (the magneto-ionic effect). Third, at great distances, where the polarization is almost random, simple receiving aerials can only extract half the power from the incident wave. Other losses are caused by residual absorption in the D layer, and in the F layer at frequencies near the MUF.

In reference 2 it is recommended that theoretical night-time field strength values should be converted to median* values by subtracting 8·9 dB. This figure is based on an analysis of 83 circuit-years of data, covering distances between 55 and 15,000 km and frequencies between 0·7 and 20 Mc/s; individual differences, however, varied from −3·1 dB to 28·5 dB. Thus considerable differences between theoretical and measured field strengths are to be expected, although the use of this factor will, on average, give a closer approximation to the observed value.

2.7. The Height of the Reflecting Layer

Changes of layer height modify the angles of arrival of the various modes and, to a lesser extent, their path lengths. Such changes must therefore be taken into consideration when comparing the performance of different types of transmitting aerials; this is discussed in detail in Section 4.

2.8. Interference Between the Direct and Ground-Reflected Waves at the Receiving Point

Since the downcoming wave is, in general, randomly polarized, the incident power is assumed to be equally divided between its vertically- and horizontally-polarized components. Listeners may therefore use vertical or horizontal aerials; if the latter are used it will be assumed that they are oriented for the best reception, in which case they respond only to the horizontally polarized component of the incident wave. Vertical aerials will of course respond only to the vertical component of the field. These two components are shown in Fig. 2 for ground of average conductivity, as a function of the angle of incidence, for a mean height of $\lambda/4$, where λ is the wavelength. Since the use of either type of aerial (vertical or horizontal) is equally probable, the average of these two components of field strength, shown dotted in Fig. 2, was used as a basis for the calculations described in the report, the mean aerial height in each case being taken as $\lambda/4$. Had a different aerial height been chosen (not exceeding about one half-wavelength), the absolute field strengths would have been different but the shapes of the curves would have been substantially the same over the range of angles of importance in h.f. propagation. The use of Fig. 2 therefore enables the performance of different transmitting arrays to be compared for any receiving aerial height likely to be encountered in practice.

3. THE CALCULATION OF FIELD STRENGTHS

Signals may be propagated over a given path by a number of different modes, all of which may contribute to the field strength at the receiving point. Because of the continual variations in the ionosphere these contributions are randomly polarized, and their total effect must be found by adding them on a power basis. The effective field strength is therefore assumed to be equal to the square root of the sum of the squares of the field strengths of the individual modes.

In such calculations it is convenient to separate the factors which depend on the type of transmitting aerial from those which depend on the propagation path; this enables different types of transmitting aerials to be readily compared. The factors which depend on the aerial will be grouped together and called the aerial factor, while the remaining factors will be called the circuit factor.

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* The value exceeded for 50% of the time.

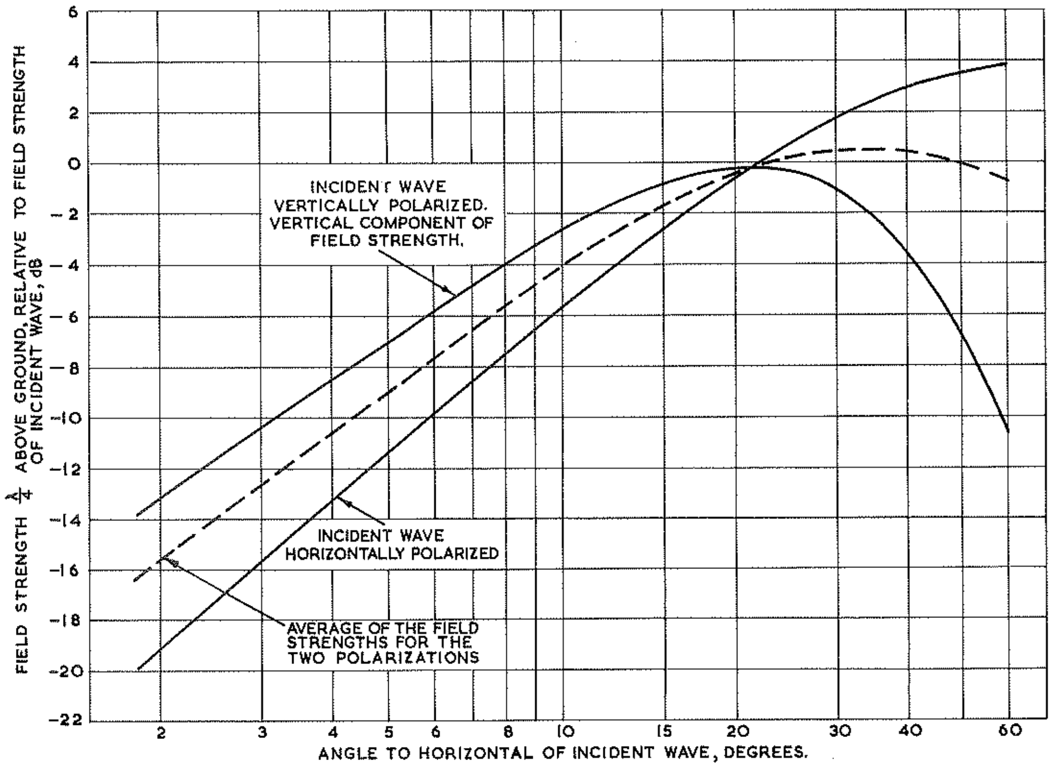

Fig. 2 - Relative field strength above ground of average conductivity

The aerial factor is the effective gain of the aerial at the angle corresponding to the mode being considered. Thus it is the sum (in dBs) of

(a) The gain of the aerial in the direction of maximum radiation. (For curtain arrays this may be obtained from reference 3).

(b) The field strength radiated in the required direction, relative to the maximum field strength. This factor is obtained from the v.r.p. of the transmitting aerial.

The circuit factor indicates the absolute field strength, for the particular mode under consideration, which would be produced by a 1 kW transmitter connected to a zero-gain aerial, in the absence of ionospheric absorption. It comprises the following factors:

(a) The attenuation due to path length. This may be obtained from Fig. 56 of reference 2, which gives the free-space field strength produced by a standard aerial radiating 1 kW, but 2·6 dB must be deducted, since the gains of B.B.C. aerials are referred to a different standard.*

(b) Ground reflexion loss. Since the loss does not depend greatly on ground conductivity the broken curve of Fig. 1 (for ground of average conductivity) was used for the calculations described in this report.

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*The standard aerial used in reference 2 is a short vertical unipole. The B.B.C. standard is a $\lambda/2$ dipole in free space

(c) A factor which relates the field strength λ/4 above the ground to that of the incident wave. The broken curve of Fig. 2 was used for the calculations described in this report.

(d) A factor of −8·9 dB to obtain the median field strength. This factor is discussed in Section 2.6.

Fig. 3 shows circuit factors as a function of distance, for the various modes which are propagated with a layer height of 320 km. These curves represent the field strengths, at λ/4 above ground level, which would be produced by a zero-gain aerial with an omnidirectional v.r.p., radiating 1 kW. It is assumed that the ground is flat both at the receiving site and at the intermediate reflexion points.

To illustrate the application of this method, the field strength produced at 10,000 km by an H4/4/0·5 array* radiating 1 kW over a land path is calculated in Table 1 below.

TABLE 1

Number of hops	3	4	5	6
Projection angle	3°	8½°	13°	17°
Transmitting aerial gain (dB)	16·1	16·1	16·1	16·1
Relative e.r.p. in direction of propagation (dB)	−7·3	−0·1	−1·6	−6·4
Aerial factor (dB)	8·8	16·0	14·5	9·7
Free-space field strength (dB rel. 1 μV/m)	26·9	26·6	26·4	26·2
Ground reflexion loss (dB)	−3·0	−9·0	−16·0	−23·0
Factor giving field strength λ/4 above ground	−12·6	−4·9	−2·3	−0·8
Factor giving median field strength (dB)	−8·9	−8·9	−8·9	−8·9
Circuit factor (dB rel. 1 μV/m)	2·4	3·8	−0·8	−6·5
Field strength (dB rel. 1 μV/m)	11·2	19·8	13·7	3·2
Relative power in each mode	13·2	95·5	23·4	2·1
Total power	134·2			
Resultant field strength due to all modes	21·3 dB rel. 1 μV/m			

4. COMPARISION OF THE FIELD STRENGTHS PRODUCED BY DIFFERENT TYPES OF ARRAYS

Since the requirements relating to the horizontal and vertical directivities of h.f. broadcasting aerials are governed by entirely separate considerations, the most convenient type of aerial is one in which the horizontal and vertical radiation patterns can be controlled independently. For this reason, the B.B.C. makes extensive use of curtain arrays comprising horizontal radiating elements; the calculations described in this report were confined to this type of array.

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*The designation Hm/n/h array indicates a curtain array consisting of n rows each containing m λ/2 elements, the lowest row being h wavelengths above ground

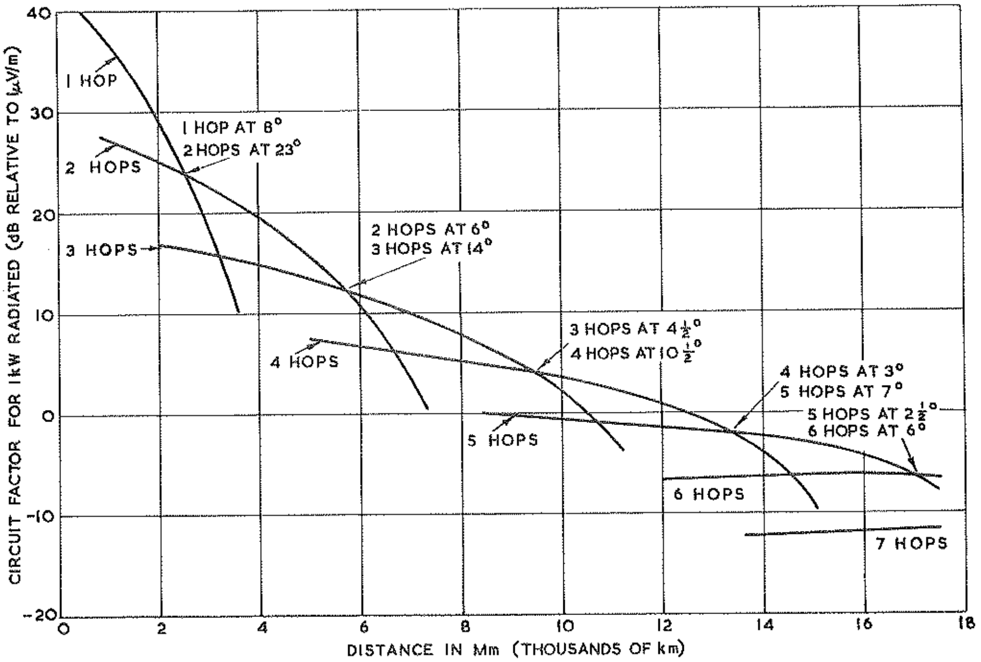

Fig. 3 - Circuit factors for ground of average conductivity. Layer height - 320 km

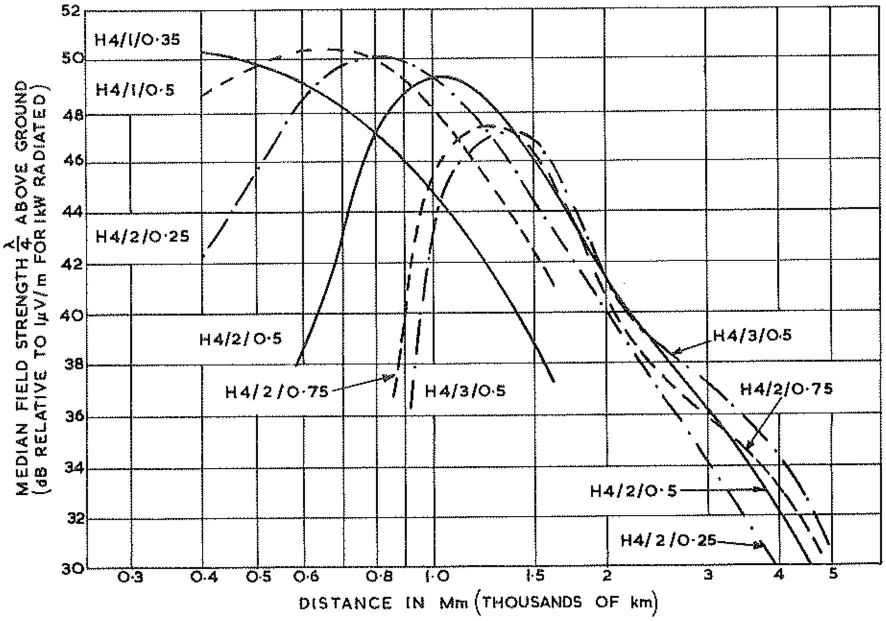

Fig. 4 - Theoretical field strengths at short and medium distances.
F layer propagation. Layer height - 260 km

Field strengths at distances ranging between 400 and 17,500 km were calculated by the method described in the previous section, for curtain arrays of 17 different types.* To enable the field strengths due to different arrangements to be compared directly, all the arrays were assumed to be 2λ wide and therefore have identical h.r.p.s. The performance of arrays of other widths can be obtained by adding or subtracting the appropriate differences in gain.[3]

Figs. 4, 5 and 6 show calculated field-strength/distance curves for the types of arrays used for short- and medium-distance broadcasting, assuming three typical F layer heights. The three sets of curves are similar to each other but are displaced, both horizontally and vertically, by amounts proportional to the differences in layer heights.

An interesting feature of short distance propagation, illustrated by these curves, is that the maximum field strength does not occur at the distance corresponding to the maximum of the transmitting aerial v.r.p. For example, an H-/2/0·25 array has a maximum radiation angle of 23° to the horizontal, and a wave projected at this angle returns to the ground at a distance of 1300 km when the layer height is 320 km. Fig. 5, however, shows that the maximum field strength occurs at the considerably smaller distance of 1000 km, both because this receiving point is nearer, and because there is less cancellation between the direct and ground-reflected waves. The most suitable array for a short distance service is one which radiates most strongly in a direction somewhat beyond the centre of the service area. It is difficult to be more specific than this because the choice of maximum radiation angle depends also on the extent of the service area.

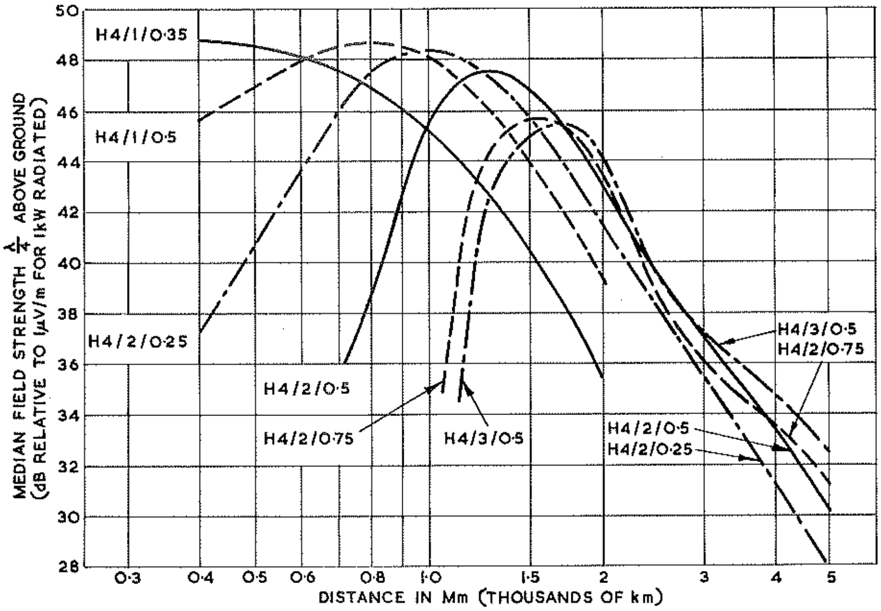

Fig. 5 - Theoretical field strengths at short and medium distances.
F layer propagation. Layer height - 320 km

*Arrays having identical vertical arrangements but different horizontal widths (for example H2/4/1 and H4/4/1 arrays) are regarded here as the same type, since they have identical v.r.p.s.

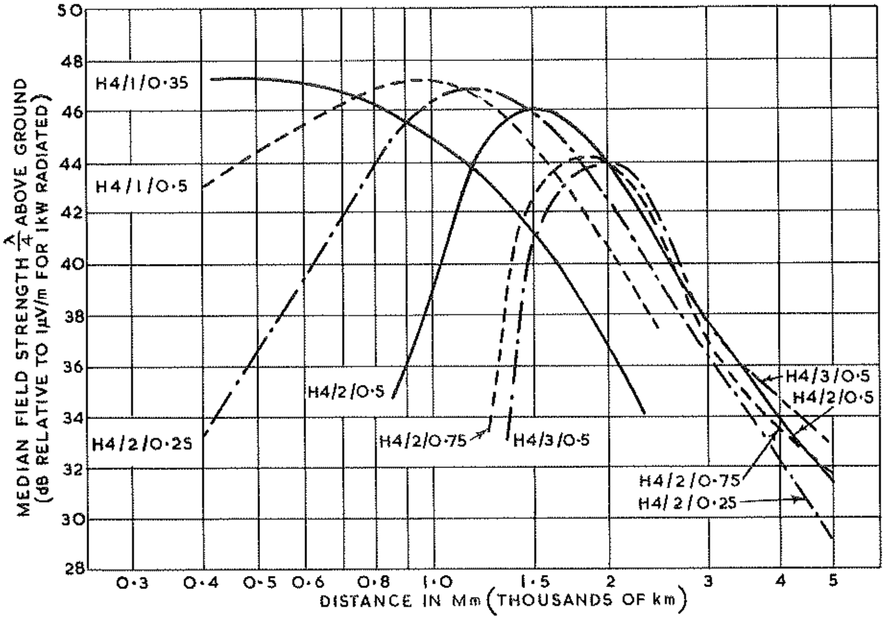

Fig. 6 - Theoretical field strengths at short and medium distances.
F layer propagation. Layer height - 380 km

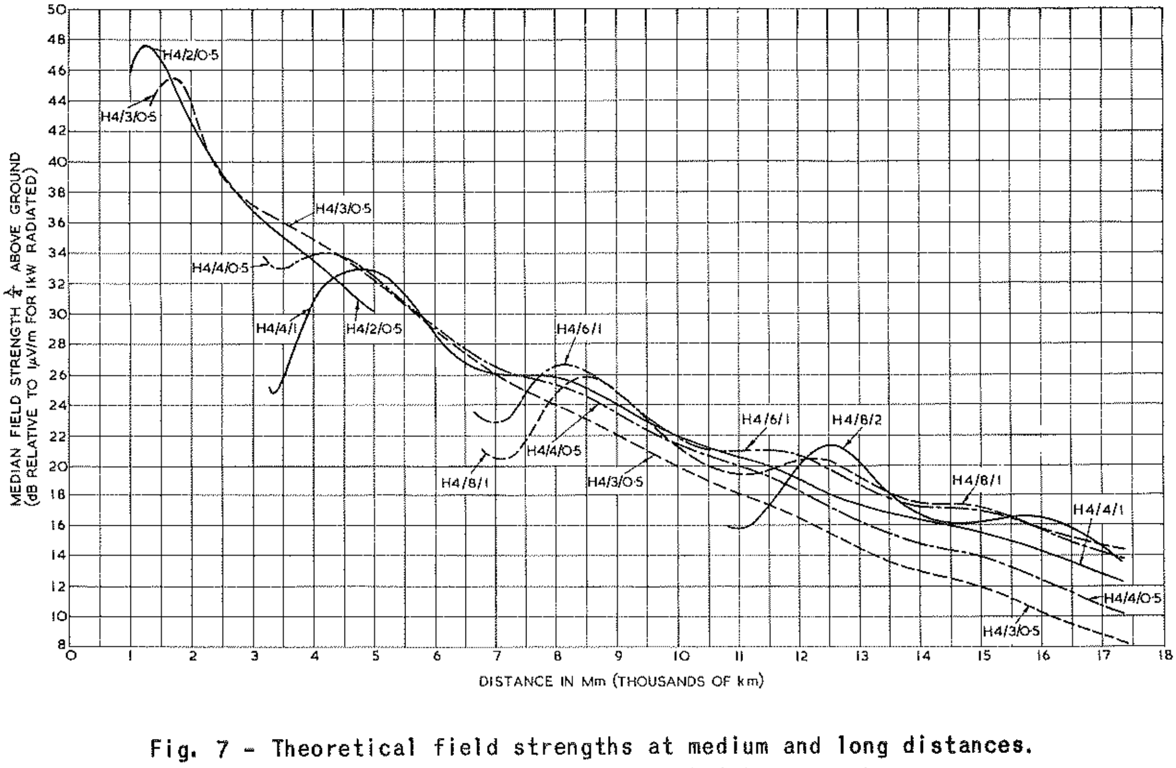

Fig. 7 - Theoretical field strengths at medium and long distances.
F layer propagation. Layer height - 320 km

Some of the results of similar calculations performed for arrays designed for medium and long distances are shown in Fig. 7; it is impossible to show all the results simultaneously. However, this is not necessary since the curves for arrays which have similar main lobes are similar in shape, because the high-angle minor lobes of practical aerials contribute very little to the received signal. Consequently, the absolute field strengths produced by arrays with similar main lobes differ by an amount equal to their difference in gain.* Now the width of the main lobe of an h.f. array, and the angle at which maximum radiation occurs, is determined largely by the angle of the first zero of the v.r.p.; this in turn is determined by the height of the centre of the array above ground. Thus medium- and long-distance arrays may be classified according to the heights of their mid-points.

Each of the curves in Fig. 7 therefore corresponds to an array with a different centre height; the salient features of their v.r.p.s are given in Table 2 below.

TABLE 2

Type of array	Height of centre above ground	Angle to horizontal of direction of maximum radiation	Angle to horizontal of first zero of v.r.p.
H-/2/0·5	0·75λ	17·5°	41·8°
H-/3/0·5	1·0λ	12·5°	30·0°
H-/4/0·5	1·25λ	9·5°	23·6°
H-/4/1·0	1·75λ	7·5°	16·6°
H-/6/1·0	2·25λ	5·5°	12·8°
H-/8/1·0	2·75λ	4·5°	10·5°
H-/8/2·0	3·75λ	3·5°	7·7°

The curve relating field strength and distance for any other type of array can be determined from Fig. 7 by modifying the curve for the array with the nearest centre height by an amount equal to the gain difference. For example, the curve for an H4/4/1·5 array may be derived from that for an H4/6/1 array by deducting 1·1 dB from all the field strength values, because both arrays have identical centre heights but differ in gain by 1·1 dB.[3]

Before studying Fig. 7 it is instructive to examine Fig. 3 in greater detail. It will be seen that the wave which travels with the smallest number of hops does not necessarily produce the greatest field strength, because of interference between the direct and ground reflected waves at the receiving point. Fig. 3 also shows that the most favourable mode will be propagated to all distances beyond 5,000 km if the power radiated is confined to angles between 3° and 14° to the horizontal. Moreover, if the service area lies beyond 12,000 km, power need only be radiated between 3° and 7° to the horizontal. These figures apply to an idealized ionosphere with a height of 320 km, but the corresponding values for other typical layer heights are not very different. Angular limits obtained in this way indicate the type of array which will give the best coverage. The most important requirement is that it should illuminate a specified range of angles rather than radiate at a particular projection angle.* No practical type of array can radiate uniformly over a sector, so a choice must be made from those arrays whose main lobes embrace the required range of angles.

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* The difference in gain between h.f. arrays having similar main lobes is almost entirely due to differences in the power radiated in the high-angle minor lobes.

Fig. 7 shows that, for distances between 2,000 and 7,000 km, the H-/3/0·5 array nearly always produces the greatest field strength. This array is to be preferred because its main lobe is wide enough to cater for the larger range of angles required at these distances. Arrays with more rows of elements (such as the H-/4/1) have main lobes which are insufficiently wide; the field strength consequently fluctuates rapidly with distance, and also with changes of layer height.

At distances greater than 7,000 km the H-/4/1 array is better because its main lobe is wide enough for advantage to be taken of its increased gain. The performance of H-/5/0·8 and H-/6/0·5 arrays are similar to that of the H-/4/1 array but they produce field strengths which are only 0·3 dB and 0·7 dB greater respectively; it is doubtful whether this increase is worth the extra complication involved. Beyond 12,000 km the H-/6/1 array offers a worth-while improvement over the H-/4/1 array, but there is little further advantage to be gained by using an H-/8/1 array, even at great distances. Although the theoretical average improvement of an H-/6/1 over an H-/4/1 array is about 1·5 dB, this gain may not be fully achieved in practice because of irregularities of the ionosphere or of the intervening terrain.

H-/6/1 and H-/8/1 arrays have projection angles of $5\frac{1}{2}^{\circ}$ and $4\frac{1}{2}^{\circ}$ respectively, and there would appear to be no advantage in using projection angles of less than 5° for very long range broadcasting arrays. This is illustrated by the curve in Fig. 7 for the H-/8/2 array; this array has a projection angle of $3\frac{1}{2}^{\circ}$.

Similar conclusions are reached if the calculations are performed for other layer heights; field strength/distance curves for three arrays and three layer heights are compared in Fig. 8. It will be seen that an increase in layer height causes slightly larger variations of field strength with distance, but the relative performance of the arrays remains substantially the same.

In all these calculations, ground of average conductivity was assumed to exist between the transmitter and receiver, since many important B.B.C. circuits are almost entirely over land. For sea paths the optimum projection angles are found to be about 10° higher, because of the much smaller 'ground' reflexion loss. However, as waves projected at these angles are less likely to be reflected by the ionosphere, it seems preferable to use the same projection angles for both land and sea paths. Other things being equal, the signal transmitted over the sea path will still be stronger because of the lower 'ground' reflexion loss.

All the calculations described have been based on the assumption that reflexion takes place at the F layer. However, normal E and sporadic E layer reflexions may sometimes be used for short-distance circuits, and sporadic E reflexions may sometimes have to be taken into account for transmission over longer distances. Since the height of the E layer is about one-third of the height of the F layer, the optimum projection angle is about the same as that for three times the

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*High-frequency arrays are often described in terms of their maximum radiation (or projection) angles. This practice is not undesirable since the beamwidth is closely related to this angle, but it should always be borne in mind that power is being radiated, and received, over a range of angles.

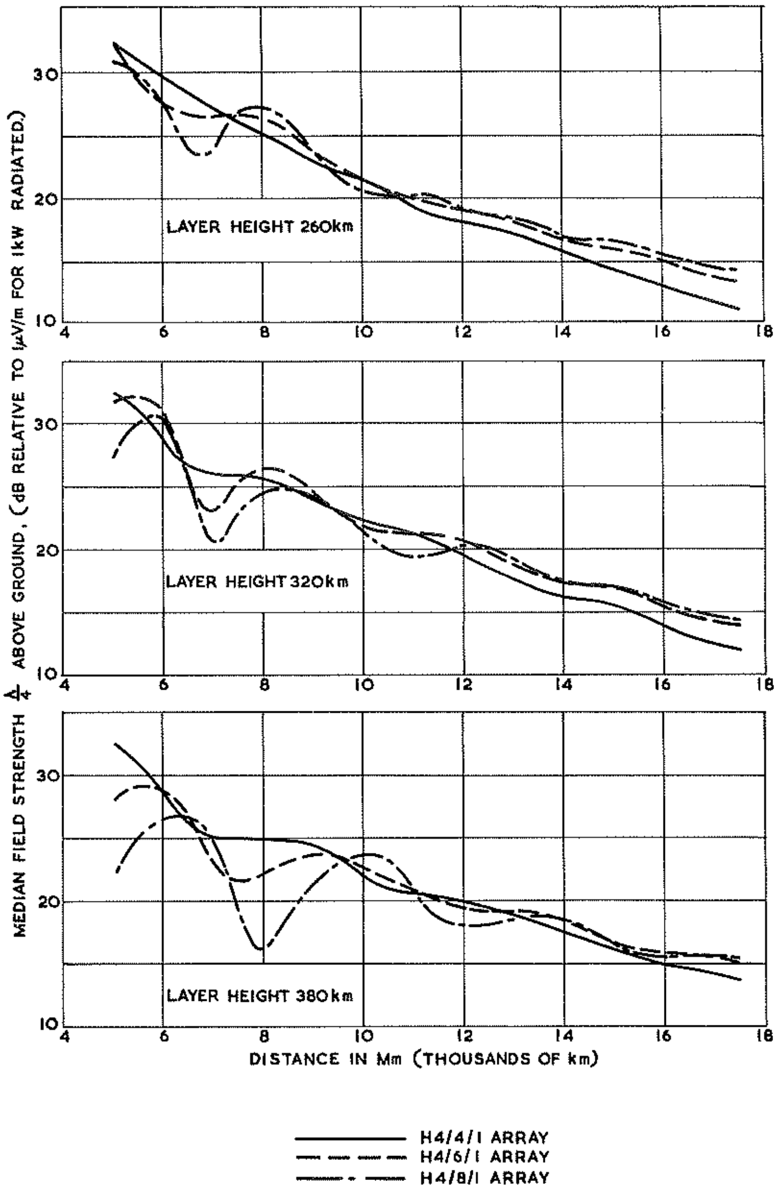

Fig. 8 - Theoretical field strengths at long distances for three layer heights

distance with F layer reflexions; correspondingly, long-range arrays designed for F layer reflexions could be used to cover one-third of their normal range, using E layer reflexions, providing the h.r.p. is suitable. Fig. 9 shows the theoretical field strengths which would be obtained with such arrays; the curves resemble those for F layer propagation (Fig. 7) but apply to shorter distances.

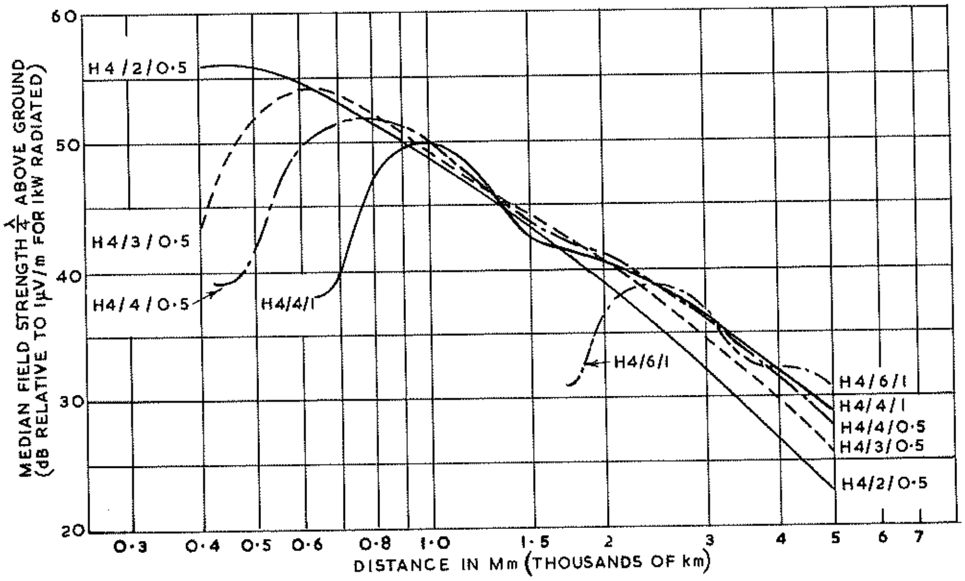

Fig. 9 - Theoretical field strengths at short and medium distances.
E layer propagation. Layer height - 110 km

Normal E layer reflexions are of principal importance during a few hours of the summer day over short-distance circuits only. Sporadic E reflexions are also of most importance during the summer day, but over a longer diurnal and seasonal period than for normal E, and are liable to affect transmission to all distances. When statistics indicate that sporadic E may occur for more than 50% of the total time it may be considered necessary to take account of its effects. Whether it is worth while providing arrays catering specially for lower angles involved depends on the importance attached to achieving the optimum results at all times, and also on finding space for the additional arrays required.

As mentioned above, long-range arrays could be used for short ranges, using normal E layer reflexions. As far as greater distances are concerned, we cannot rely on continuous sporadic E layer reflexions; except in a localized zone of the ionosphere they would only occur (sporadically) for a limited diurnal and seasonal time. In any case, the long-distance arrays radiate an appreciable amount of energy at the low angles suitable for sporadic E layer transmission; there seems no point, therefore, in designing long-distance arrays specially for sporadic E layer reflexions.

5. CONCLUSIONS

The transmitting aerial requirements for h.f. broadcasting differ from those for point-to-point communication systems because the typical receiving aerial is insensitive at low angles. Consequently, more energy must be propagated at higher angles, and the width of the main lobe must be such that at least one mode is propagated over the range of distances to be covered, for all the layer heights which are likely to be encountered. For long distances, projection angles of 5-8° appear to be the most satisfactory. There is no apparent advantage in using lower projection angles, even though higher transmitting aerial gains may be achieved; this conclusion is consistent with measurements which have been carried out over B.B.C. circuits.

For distances up to 2,000 km, the most suitable type of array depends on the actual range of distances involved and on the layer height likely to be encountered during the transmission period. Arrays for F layer propagation may be selected from Figs. 4-6 of this report, and for E layer propagation from Fig. 9 of this report.

F layer propagation nearly always applies for distances greater than 2,000 km, and the recommendations for these distances which follow are based on this assumption. For distances between 2,000 and 7,000 km the most suitable type of array is the H-/3/0·5. (This array is quite satisfactory for distances up to 10,000 km, but at this distance the field strength it produces is about 2 dB less than that given by an H-/4/1 array.) For all distances beyond 7,000 km the H-/4/1 array is satisfactory. The performance of H-/5/0·8 and H-/6/0·5 arrays are very similar to that of the H-/4/1 array, but as the field strengths which they produce are only slightly greater (0·3 dB and 0·7 dB respectively) their increased complication may not be justified.

If the service area is confined to distances greater than 12,000 km, an increase of 1·5 dB may be obtained by using an H-/6/1 array; however this gain increase may not be fully realized in practice because of ionospheric irregularity.

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